CHAPTER 1

INTRODUCTION

1.1 PROPAGATION EFFECTS ON SYSTEM PERFORMANCE

1.1.1 Performance of Earth-Space Links

A fundamental requirement for satisfactory satellite communications is the maintenance of a sufficient signal-to-noise ratio. Propagation effects may cause transmission losses which adversely affect this ratio, The received carrier power C on a path of length d is givenby

$$C = \frac{\text{‘T ‘T ‘R}}{4\pi d^2 L} \tag{1.1}$$

Here P_T is the power supplied to the transmitting antema, G_T is the gain of the transmitting antenna, AR is the effective area of the receiving antenna, and L is a loss factor which includes all losses, including propagation losses, that are not otherwise taken into account. If the losses included in L reduce C to 0.5 of what its value would be in the absence of losses, for example, L would have a value of 2. Transmission losses are commonly specified in terms of the losses exceeded for a certain small percentage, such as 0.01 percent, of a year or worst month.

Equation 1.1 can be-converted to

$$C = \frac{\text{‘T ‘T } G_R}{\text{‘FS } L} \tag{1.2}$$

where, for the receiving antenna, use has been made of the relation between gain and effective area A_{eff}, namely

$$G = 4\pi A_{eff} / \lambda^2 \tag{1.3}$$

The quantity L_{FS} is the so-called free-space loss and is given by

$$\text{‘FS} = (4\pi d/\lambda)^2 \tag{1.4}$$

In Eqs. (1 .3) and (1 .4), λ is wavelength. The noise power X in watts at the receiving antenna terminals is given by

$$X = k T_{Sys} B \tag{1.5}$$

where k is Boltzmann's constant (1.38×10^{-23} J/K), T_{Sys} is the system noise temperature (K), and B is bandwidth (Hz). The ratio C/X is given by

$$C/X = \frac{P_T G_T G_R}{L_{FS} L k T_{sys} B} = \frac{(EIRP)\, G_R}{L_{FS} L k T_{sys} B} \tag{1.6}$$

where EIRP (effective isotropically radiated power) has been substituted for the product $P_T G_T$. In some cases, however, P_T is taken to be the transmitter or power amplifier output rather than the transmitting antenna input. In that case

$$EIRP = P_T G_T / L_T \tag{1.7}$$

where L_T accounts for losses in switches, filters, cables, or waveguides between the power amplifier and the antenna terminals. The quantity C/X is commonly expressed in dB (decibel) values and then takes the form of

$$(C/X)_{dB} = (EIRP)_{dBW} - (L_{FS})_{dB} - L_{dB} + (G_R/T_{sys}) - k_{dBW} - B_{dB} \tag{1.8}$$

In terminology commonly used, this relation applies to RF (radio-frequency) links and their power budgets. In Eq. (1 .8) k is taken to be the product of k as defined above times a 1 K temperature range times a 1 Hz bandwidth so that it has units of dBW (power measured in dB with relation to one watt). Then T_{Sys} and B are treated as nondimensional quantities expressed in dB above unity. The L_{FS} value in dB is given by

$$(L_{FS})_{dB} = 10 \log (4\pi d/\lambda)^2 = 20 \log (4\pi d/\lambda) \tag{1.9}$$

The carrier power-to-noise density ratio, C/X_o, where X_o is noise power per Hz , is frequent 1 y used. It differs from C/X only by the factor B, representing bandwidth, and is thus given by

$$C/X_o = \frac{(EIRP)\, G_R}{L_{FS}\, L\, T_{sys}\, k} \qquad (1.10)$$

Some satellites serve a wide geographical area in which a number of earth stations are located. In such a case the satellite transmitter gain G_T and the corresponding value of EIRP that are used must be the appropriate value, It can not be assumed that the maximum antenna gain, for the center of the main beam, is the value to use. For satellites that are operational or for which antenna designs are available, plots showing contours of constant EIRP may be available (Fig. 10.6). These plots, commonly referred to as footprints, allow selecting the proper value of G_T or EIRP to use.

As the system designer may be required to provide a certain C/X. ratio over a certain area A_{cov}, it is instructive to show the relation between these parameters and other system parameters. A relation accomplishing this purpose has been supplied by Pritchard (1977) who gives the following expression.

$$A_{Cov}\,(C/X_o) \propto P_T A_R / L T_{sys} \qquad (1.11)$$

A similar expression involving bandwidth Band C/X is

$$A_{cov}\, B\, (C/X) \propto P_T A_R / L T_{sys} \qquad (1.12)$$

Note that these relations show proportionality rather than equality. Pritchard has stressed that Eqs. (i. 11) and (1. 12) are fundamental to appreciating the essential problems of space communication. They display clearly the roles of L and T_{sys} in determining system performance. L is used here primarily to account for propagation losses but also for pointing error losses, etc. T_{sys} is not strictly a propagation effect but plays a comparable role. ‘ A derivation and further discussion of Eq. (1. 1 1) is given in Sec. 10.4.

1,1,2 Determination of Distance and Elevation Angle of Satellite

Satellite orbits are treated analytically by Pratt and Bostian (1986) and Pritchard and Sciulli (1986). A geostationary satellite rotates above the equator with an angular velocity equal to that of the Earth and thus appears stationary with respect to the Earth. We take the altitude of geostationary satellites to be 35,786 km above sea level. Unless an earth station is directly under a satellite, however, the distance d of the satellite will be larger than 35,786 km. The value of d can be established by use of the law of cosines of plane trigonometry, Consider first that the earth station is on the same longitude as the subsatellite point at 0 deg of latitude. The subsatellite point is located where a straight line from the satellite to the center of the Earth intersects the Earth's surface. Referring to Fig. 1.1

$$d^2 = r_o^2 + (h + r_o)^2 - 2\, r_o\, (h + r_0) \cos \theta' \qquad (1.13)"$$

where θ' is latitude. The equatorial radius of the Earth is 6378.16 km, the polar radius is 6356.78 km, and the mean radius is 6371.16 km (Allen, 1976). To obtain the most accurate value of d, it would be necessary to take into account the departure of the Earth from sphericity, but an approximate value of d can be obtained by taking r_o, the earth radius, to be 6378 km and h, the height of the satellite above the Earth's surface, to be 35.786 km in Eq. (1.13). It may be convenient to divide all terms-by $(h + r_0)^2$ or $(42,164)^2$ giving

$$[d/(h + r_0)]^2 = f^2 + 1 - 2f \cos \theta' \qquad (1.14)$$

where $f = r_0/(h + r_0) = 0.1513$. Once d is known then all three sides of a triangle are known and the angle ψ can be determined by applying the law of cosines again, The applicable equation is

$$(h + r_0)^2 = d^2 + r_o^2 - 2\, r_o\, d \cos \psi \qquad (1.15)$$

The elevation angle θ measured from the horizontal at the earth station is equal to ψ - 90 deg.

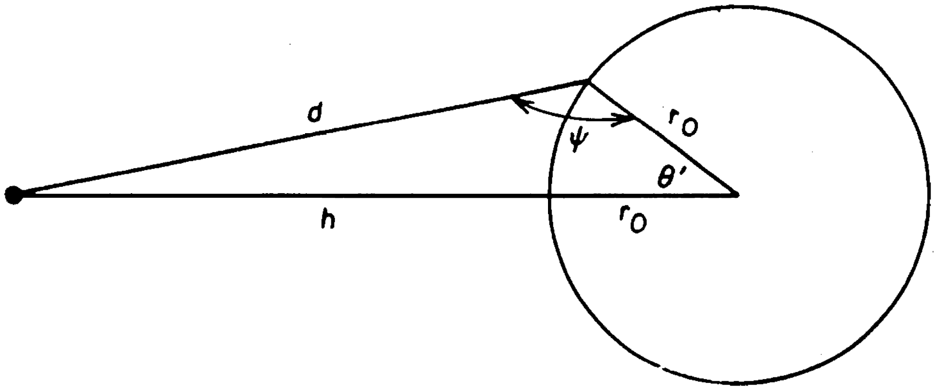

Figure 1.1 Geometry for calculation of distance. d of satellite from earth station.

For an earth station not on the same meridian as the subsatellite point, one can use

$$Cos\ Z = Cos\ e'\ Cos\ \phi' \tag{1.16}$$

in Eq. (1.13) in place of cos θ' where ϕ' is the difference in longitude between subsatellite point and earth station. Cos Z is the angular distance of a great-circle path for the special case that one of the end points is at 0 deg latitude (Fig. 1.2). Also the expression follows from the "law of cosines for sides" of spherical trigonometry (Jordan, 1986). The angle α of Fig. 1.2 for an earth-space path can be determined by using

$$cos\ a = \tan \theta' \cot Z \tag{1.17}$$

another relation applying to a right spherical triangle (Jordan, 1986). The angle a is shown in Fig. 1.2a for an earth station located to the east of the subsatellite point. The azimuth angle measured from north in this case would be 1 80 deg + a. For an earth station location to the west of the subsatellite point as in Fig. 1.2b, the azimuth angle from north is 180 deg - α. As an example, calculations for Boulder, Colorado. latitude 40 deg N, longitude 105 deg W and for Satcom-2, located at 119 deg W, with cos Z = cos 40 deg times cos 14 deg = 0.743, give d = 37,668 km, elevation angle θ = 41.46 deg, and azimuthal angle = 201.2 deg.

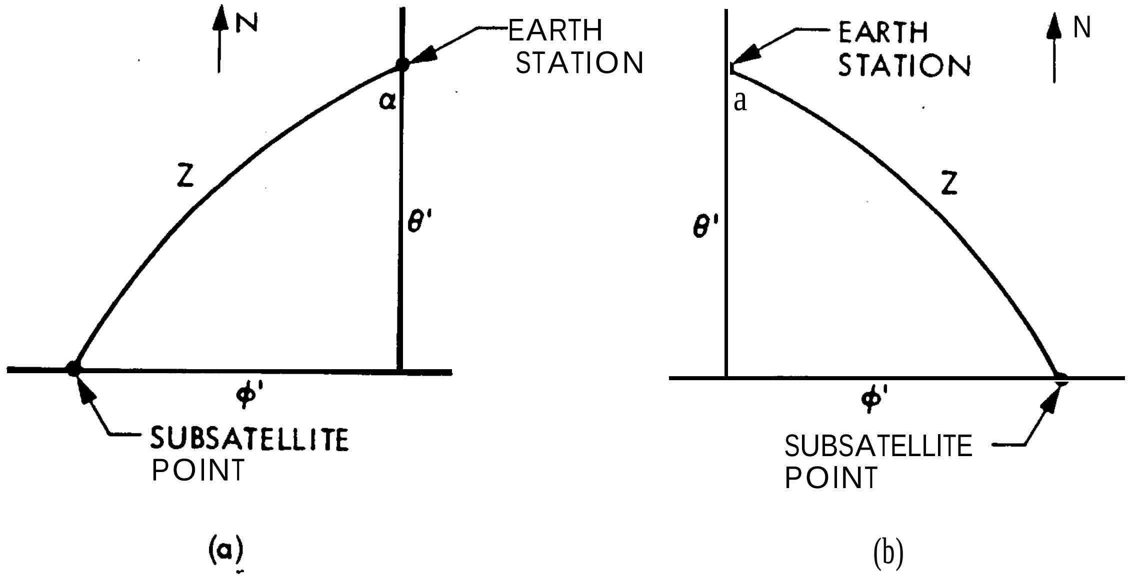

Figure 1.2 Projection of right spherical triangles on Earth's surface.

In Eq. (1. 14), r_o was taken as the Earth's equatorial radius, but values of r and h can be adjusted for elevations significantly above sea level. 'Local topography affects the angle of the path above the local horizon and can be taken into account to determine this angle for a particular location. Propagation effects are a function of elevation angle and tend to become more serious with decreasing elevation angle. An elevation angle of 5 deg may be considered to be the minimum elevation angle that should normally be used. The procedure described above for determining distance and elevation and azimuthal angles, essentially the same as that described by Dougherty (1980), is presented as suitable for link analysis and consideration of propagation effects rather than for precise aiming of antennas.

1.13 Propagation and Related Effects

Relatively small margins are utilized for satellite communications, and it is important to use no larger a margin than necessary, Thus it is important to have as accurate information as practical about the propagation factors contributing to L even for the case of effects which might appear to be minor.

Frequencies in roughly the 1 to 4 GHz range tend to be affected only slightly by the Earth's atmosphere, but even in this range it is important to know what the magnitudes of the effects are. Moving to higher frequencies, attenuation and noise due to rain, clouds, and atmospheric gases increase, These effects may become limiting factors above 1 0 GHz. The ionospheric effects of Faraday rotation, amplitude and phase scintillation, and absorption, on the other hand, become increasingly significant with decreasing frequency.

Depolarization or cross polarization may occur in propagation through the atmosphere or in reflection from terrestrial features. These terms refer to a degradation or change in polarization as from purely vertical linear polarization to linear at an angle slightly different from vertical. This latter polarization is equivalent to a combination of vertical and horizontal polarization. The power converted to the orthogonal polarization may interfere with a channel having that polarization and make less effective the practice of frequency "reuse" (using the same frequency for two orthogonal polarizations in this case). An effect that is important to ranging and navigation systems is the excess range delay, above that encountered in propagation through a vacuum, that is encountered in propagation through the Earth's ionosphere and troposphere.

Electromagnetic radiation emitted by the atmosphere, an important part of sky noise, is not strictly a propagation effect but is closely related and increases when attenuation increases. As is evident from Eqs. (1. 11) and (1. 12), T_{sys} affects system performance directly, Sky noise contributes to T_{sys}. When using a low noise receiving system, only a slight increase in sky noise may increase T_{Sys} significantly. It is important to know T_{Sys}, as well as L, as accurately as practical.

A few references of a general nature, concerning either satellite systems or propagation effects, are appropriate for mention here. A comprehensive treatment of satellite communication engineering has been presented by Miya (1981), and Freeman (1981) includes satellite systems, as well as HF radio, line-of-sight terrestrial systems, and troposcatter systems, in his Telecommunication Transmission Handbook. Thompson (19? 1) prepared an Atmospheric Transmission Handbook covering the range. from 3 kHz to 3,000 THz. Recent references on satellite communications have been provided by Feher (1983), Pratt and Bostian (1986), and Pritchard and Sciulli (1986). Hall (i 979) presented a summary of tropospheric effects on radio communication, and Ippolito (1986) concentrated on the role of radio wave propagation in satellite communciations. NASA Reference Publication 1082 (Ippolito, Kaul, and Wallace, 1983) treats propagation effects at frequencies above 10 GHz, but many of the concepts and much of the material presented is pertinent to a broader range of frequencies. Evans (1986) has reviewed the development of international satellite communications over the past two decades and considered likely trends in satellite systems as these may evolve with relation to fiber-optic cables.

1.2 FREQUENCY ASSIGNMENTS AND APPLICATION BELOW 10 GHZ

Frequencies below 10 GHz are used for a variety of purposes involving earth-space paths as shown in Table 1.1. The categories of service are actually little different for frequencies above 10 GHz. This handbook treats propagation effects between 100 MHz and 10 GHz, and a listing of frequency allocations for space service in this band is given in Table 1.2. The entries in this table are from the Final Acts of the World Administrative Radio Conference, Geneva, 1979, Volume 1E (ITU, 1982, Revised 1985) for Region 2, which comprises North and South America and portions of the Atlantic and Pacific Oceans. Allocations for Region 1 (Europe, Africa, and Northern Asia) and Region 3 (Southern Asia and the South Pacific, including Australia and New Zealand) are similar but differ in details. The reference includes numerous footnotes giving information about exceptions for particular countries and periods, but information from the footnotes is omitted from Table 1.2 unless otherwise indicated. For brevity we use Uplink and Downlink in place of Earth-to-space and space-to-Earth as in the original publication. Allocations are also given in the Manual of Regulations and Procedures for Federal Radio Frequency Management (NTIA, 1986) and in the FCC Rules and Regulations.

The INTELSAT satellite system uses frequencies near 6 GHz for the uplink and frequencies near 4 GHz for the downlink, and allocations used by INTELSAT are included in Table 1.2 as entries for fixed satellites. Note, that a number of space services utilize lower frequencies. Included among these services are space

Table 1.1 Satellite Services (ITU, 1982, Revised 1985)

Aeronautical Mobile Satellite
Aeronautical Radionavigation Satellite
Amateur Satellite
Broadcasting Satellite
Earth Exploration Satellite
Fixed Satellite
Inter Satellite
Land Mobile Satellite
Maritime Mobile Satellite
Maritime Radionavigation Satellite
Meteorological Satellite
Mobile Satellite
Radiodetermimtion Satellite
Radionavigation Satellite
Space Operations
Standard Frequency and Time Signal Satellite

Table 1.2 Frequency Allocations for Space Services (ITU, 1982, Revised 1985).

Frequency (MHz)	Services
437-138	Space Operations and Research (Downlink) Meteorological Satellite (Downlink)
138 -143.6	Space Research (Downlink)
143.6 -143.65	Space Research (Downlink)
143.65-144	Space Research (Downlink)
144-146	Amateur Satellite
149.9-150.05	Radionavigation Satellite
267-272	Space Operation (Downlink)
272-273	Space Operation (Downlink)
322 -328.6	Radio Astronomy
399.9-400.05	Radionavigation Satellite
400.05-400.15	Standard Frequency and Time Signal Sat.
400.15-401	Meteorological Satellite (Downlink) Space Research and Operation (Downlink)
401-402	Space Operation (Downlink) Earth Exploration Satellite (Uplink) Meteorological Satellite (Uplink)
402-403	Earth Exploration Satellite (Uplink) Meteorological Satellite (Uplink)
406 -406.1	Mobile Satellite (Uplink)
406.1-410	Radio Astronomy
460-470	Meteorological Satellite (Downlink)
608-614	Radio Astronomy (Footnote 688) Mobile Satellite (Uplink)
620-790	Broadcasting Satellite (Footnote 693)

Table 1.2 Frequency Allocations for Space Services (continued).

Frequency (MHz)	Services
/306 -890	Mobile Satellite (Footnotes 699,700,70 1)
942-960	Mobile Satellite (Footnotes 699, 701)
1215-1240	Radionavigation Satellite (Downlink)
1240-1260	Radionavigation Satellite (Downlink)
1370.-1400	Space Research (Passive) Earth Exploration Satellite (Footnote 720)
1400-1427	Radio Astronomy (1420 MHz H line) Earth Exploration Satellite (Passive) Space Research (Passive)
1427-1429	Space Operation (Downlink)
1525-1530	Space Operation (Downlink) Earth Exploration Satellite
1530-1535	Space Operation (Downlink) Maritime Mob. Sat. (Downlink, Foot. 726) Earth Exploration Satellite
1535-1544	Maritime Mobile Satellite (Downlink)
1544-1545”	Mobile Satellite (Downlink)
1545-1559	Aeronautical Mobile Satellite (Downlink)
1559-1610	Radionavigation Satellite (Downlink)
1626.5 -1645.5	Maritime Mobile Satellite (Uplink)
1645.5 -1646.5	Mobile Satellite (Uplink)
1646.5-1660	Aeronautical Mobile Satellite (Uplink)
1660 -1660.5	Aeronautical Mobile Satelllte (Uplink) Radio Astronomy
1660.5 -1668.4	Radio Astronomy Space Research (Passive)

Table 1.2 Frequency Allocations for Space Services (continued).

Frequency (MHz)	Services
1668.4 -1670	Radio Astronomy
1670-1690	Meteorological Satellite (Downlink)
1690-1700	Meteorological Satellite (Downlink)
1700-1710	Meteorological Satellite (Downlink)
1718.8 -1722,2	Radio Astronomy (Footnote 744) .
1758-1850	Space Operation and Research (Uplink, Footnote 745)
1770-1790	Meteorological Satellite (Footnote 746)
2025-2110	Space Operation and Research Earth Exploration Satellite (Footnote 747)
2110-2120	S ace Research (Deep Space Uplink) (footnote 748) Space Research and Operation (Uplink) (Until 31 Dec. 1 990, Footnote 749)
2200-2290	Space Research and Operation Earth Exploration Satellite (Footnote 750)
2290 - 2300	Space Research (Deep Space Downlink)
2500-2535	Mobile Satellite (Downlink, Footnote 754)
2500-2655.	Fixed Satellite (Downlink) Broadcasting Satellite
2655-2690	Fixed Satellite (Downlink and Uplink) Broadcasting Satellite Earth Exploration Satellite (Passive) Radio Astronomy and Space Research
2690-2700	Earth Exploration Satellite (Passive) Radio Astronomy and Space Research
3400-3500	Fixed Satellite (Downlink)

Table 1.2 Frequency Allocations for Space Services (continued).

Frequency (MHz)	Services
3500-3700	Fixed Satellite (Downlink)
3700-4200	Fixed Satellite (Downlink)
4202	Standard Frequency and Time (Downlink) (Footnote 791)
4500-4800	Fixed Satellite (Downlink)
4800-4900	Radio Astronomy
4990-5000	Radio Astronomy Space Research (Passive)
5250-5255	Space Research
5650-5725	Space Research (Deep Space)
5725-5850	Fixed Satellite (Uplink)
5830-5850	Amateur Satellite (Downlink) (Footnote 808)
5850-5925	Fixed Satellite (Uplink)
5925-7025	Fixed Satellite (Uplink)
6427	Standard Frequency and Time (Uplink) (Footnote 791)
7125-7155	Space Operation (Uplink, Footnote 810)
7145-7190	S ace Research (Deep Space Downlink) (#'ootnote811)
7250-7300	Fixed Satellite (Downlink) Mobile Satellite (Downlink)
7300-7450	Fixed Satellite (Downlink) Mobile Satellite (Downlink)
7450-7550	Fixed Satellite (Downlink) Meteorological Satellite (Downlink) Mobile Satellite (Downlink)

Table 1.2 Frequency Allocations for Space Service (continued).

Frequency (MHz)	Services
7550- 77s0	Fixed Satellite (Downlink) Mobile Satellite (Downlink)
7900-7975	Fixed Satellite (Uplink) Mobile Satellite (Uplink)
7975-8025	Fixed Satellite (Uplink) Mobile Satellite (Uplink)
8025-8175	Fixed Satellite (Uplink) Earth Exploration Satellite (Downlink) Mobile Satellite (Uplink)
8175 - 8215	Earth Exploration Satellite (Uplink) Fixed Satellite (Uplink) Meteorological Satellite (Downlink) Mobile Satellite (Uplink)
8215-8400	Earth Exploration Satellite (Downlink) Fixed Satellite (Uplink) Mobile Satellite (Uplink)
8400-8450	Space Research (Deep Space Uplink)
8450-8500	Space Research (Downlink)
9975-10025	Meteorological Satellite (Footnote 828)

research, involving the use of telemetry for transmitting data to the Earth, and space operations, including 'the functions of tracking and command. The frequency ranges of 2110 to 2120 MHz, 2290 to 2300 MHz, 5650 to 5725 MHz, and 8450 to 8500 MHz are listed as being for deep-space research. Plans for the proposed satellite power system for collecting solar energy called for transmission of energy to the Earth at 2450 MHz. but implementation of such a system is questionable.

Parties involved in the development of land-mobile satellite systems in the United States and Canada have wanted to use portions of the 806-890 MHz band that have been held in reserve, but an FCC decision of July 28, 1986 allows only for L-band operation in the United States for land-mobile satellite service. The Aeronautical and Mobile Satellite services will share on an equal basis (co-primary) the 1549 .5-1558.5 MHz band for space to mobile platform transmission and the 1651-1660 band for mobile platform to space transmission. The Aeronautical Mobile Satellite service is designated as the primary occupant and Mobile Satellite service will be a secondary service, operated on a non-interference basis, in the 1545-1549. 5 MHz band for space to mobile platform operation with 1646-1651 MHz used for mobile platform to space operation, Some of the 806-890 MHz band that was previously held in reserve was allocated to the Public Safety Radio Service, and four MHz (849-85 1 and 894-896) were kept in reserve.

The version of Table 1.2 of this edition includes a number of entries that were not in the original 1979 version of the table, especially in the 7250-8175 MHz range where Mobile Service was added to the previous listings. NTIA (1986) shows the allocations in this frequency range to be for governmental use in the United States.

Listings or logs of operational or planned geostationary satellites are published from time to time in the COMSAT Review and elsewhere. The texts by Pratt and Bostian (1986) and Pritchard and Sciulli (1986) also include information of this type.

1.3 STRUCTURE OF THE EARTH'S ATMOSPHERE .

Earth-space paths traverse both the Earth's troposphere and ionosphere, and the characteristics of the atmospheric regions are thus pertinent to satellite communications.

Troposphere

Temperature decreases with increasing altitude in the troposphere, but temperature inversion layers provide exceptions to this general characteristic. The thickness of the troposphere varies but it extends to about 10 km over the poles and 16 km over the equator. The upper limit of the troposphere is known as the tropopause. A plot of atmospheric temperature versus altitude is shown in Fig. 1.3.

Atmospheric pressure tends to decrease exponentially with altitude in accordance with

$$p = p_o e^{-h/H} \tag{1.18}$$

where h is the height above a reference level where the pressure is p_0. The scale height H is not a constant as it is a function of temperature T, the average mass of the molecules present, and the acceleration of gravity g as indicated by

$$H = kT/mg \tag{1.19}$$

where k is Boltzmann's constant.

The rate of change of temperature with altitude in a dry atmosphere in an adiabatic state (involving no input or loss of heat energy) is given by dT/dh = -9.8 deg C/km. The dry adiabatic rate of change of temperature with height is of interest because the stability or instability of the atmosphere is determined in large part by the relative values of the actual rate of change of temperature with altitude and the dry adiabatic rate. If the actual lapse rate of the atmosphere (rate of decrease of temperature with altitude) is 9.8 deg C/km, a parcel of air that is originally in equilibrium with its surroundings and which is then moved upwards or downwards will tend to remain in equilibrium, at the same temperature as its surroundings. The parcel of air will then not be subject to an restraining or accelerating force. Such a lapse rate of temperature is referred to as neutral. If the actual lapse rate of the atmosphere is greater than 9.8 deg C/km, a rising parcel of air will tend to cool onlyat the adiabatic rate and be warmer than its surroundings. As a result it will be lighter than the air around it and will be accelerated still further upwards, The air in this condition is unstable. If the lapse rate is less than 9.8 deg C/km, a parcel moved upwards will tend to cool at the adiabatic rate and be cooler than its surroundings, Thus it is subject to a force that inhibits vertical motion. A lapse rate less than 9.8 deg C/km is a stable lapse rate.

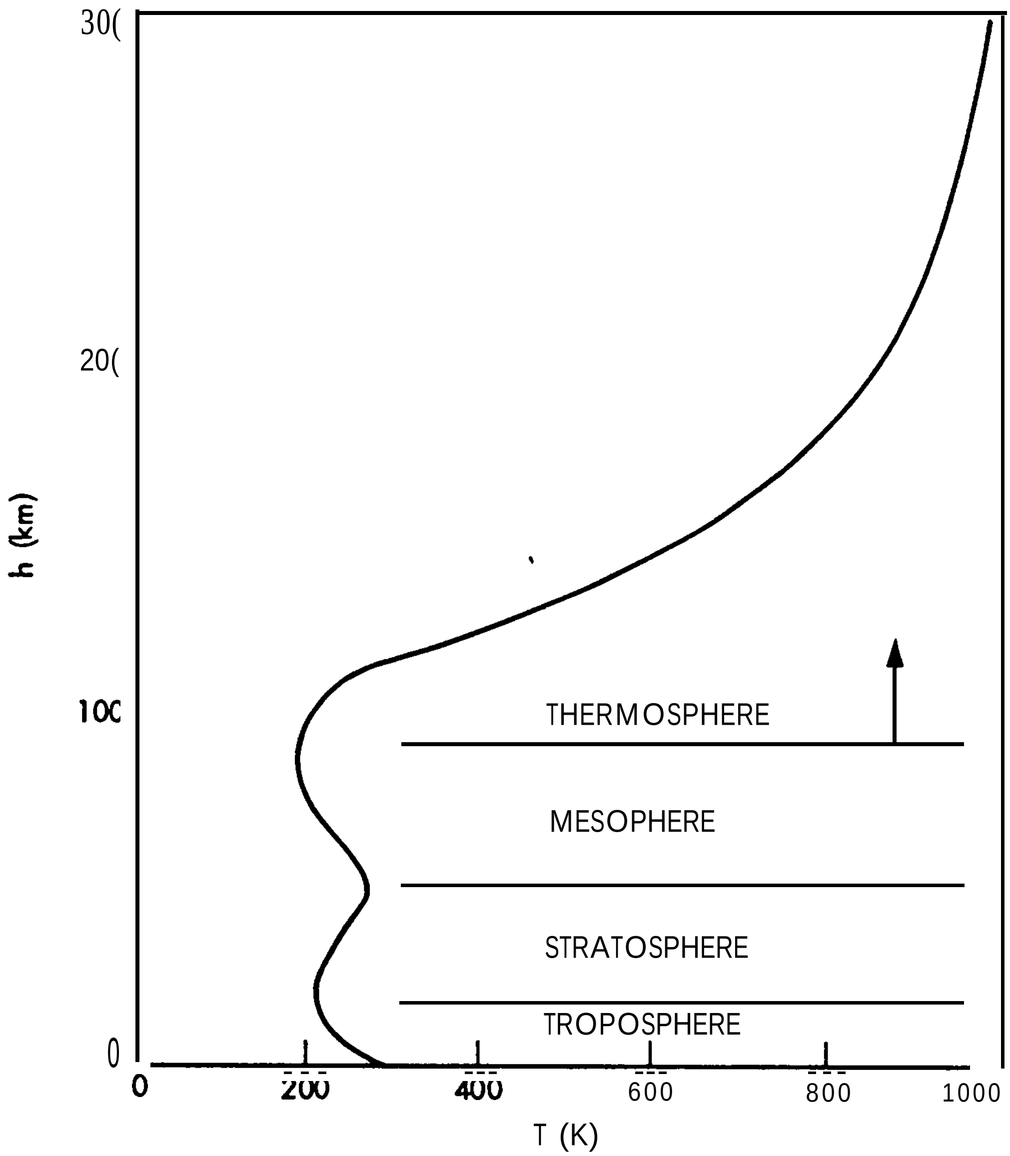

Figure 1.3 Atmospheric temperature versus altitude (values from U.S. Standard Atmosphere, 1976).

In an inversion layer temperature increases with altitude, and such a layer is highly stable. All vertical motions are strongly inhibited inan inversion layer, and pollution emitted below the layer tends to be confined below it. If a source of water vapor exists below an inversion layer, the vapor tends to be confined below the layer also with the result that a large decrease in index of refraction may be encountered in upward passage through an inversion layer. The occurrence of inversion layers may have an important effect on low-angle earth-space communication paths (Sees. 3.2 and 3.3).

Inversions tend to develop at night and in the winter, especially under conditions of clear sky as in the desert at night and in the arctic and subarctic in winter. Inversions may also form when warm air blows over a cool surface such as an ocean surface. Subsiding air is another cause of inversions, and this type of inversion is common because descending air is associated with developing or sempermanent anticyclones. The Pacific coast of the United States lies along the eastern edge of a semipermanent anticyclone that forms in the Pacific; this occurrence is a major factor in causing the pollution problems of the Los Angeles area.

Model atmospheres have been developed to present the best available estimates of the average values of pressure, density, temperature, and other parameters. One such model atmosphere is the U.S Standard Atmosphere (1976). Temperature tends to decrease on the average at a rate of 6.5 deg C/km, which is less than the dry adiabatic rate. When rainfall occurs at the Earth's surface a transition to ice and snow particles tends to occur at the height where the 0 deg C isotherm is reached. Water drops cause much higher attenuation than do ice particles and snow, so the O deg C isotherm marks the upper boundary of the region where most attenuation due to precipitation occurs.

Stratosphere, Mesosphere, Thermosphere

Above the troposphere temperature increases with height, to a maximum near 50 km, as a result of the absorption of solar ultraviolet radiation by ozone (Fig. 1.3). This region of increasing temperature with height is known as the stratosphere. The mesosphere, a region of decreasing temperature with height, occurs above the stratosphere and extends to about 85 km.

Above 85 km is the thermosphere, in which temperature again increases with height as a result of the dissociation of atmospheric gases by solar ultraviolet radiation, Above 300 km temperatures change little with height for a considerable distance. Below about 100 km temperature changes little with time, but the temperature above 120 km may vary by nearly a factor of 3 to 1, being highest in the daytime near the peak of the 11-year sunspot cycle.

The characteristic of the thermosphere of most importance to satellite communication is not the temperature structure itself but the ionization that. occurs there. On the basis of the ionization, the region is known as the ionosphere. The ionosphere has a lower limit of about 60 km, and it thus includes part of the mesosphere as well as the thermosphere.

Ionosphere

The ionosphere extends from about 60 km to a not very well defined upper limit of about 500 to 2000 km above the Earth's surface, As geostationary satellites operate at an altitude of about 35,786 km, transmissions to and from these satellites pass through the entire ionosphere. The ionosphere, which is ionized by solar radiation in the ultraviolet and x-ray frequency ranges, is an ionized gas *or* plasma containing free electrons and positive ions so as to be electrically neutral. Only a fraction of the molecules are ionized, and large numbers of neutral molecules are also present. It is the free electrons that affect electromagnetic wave propagation in the frequency range considered in this report (100 MHz to 10 GHz),

Because different portions of the solar spectrum are absorbed at different altitudes, the ionosphere consists of several layers or regions. The layers are not sharply defined, distinct layers, and the transition from one to the other is generally gradual with no very pronounced minimum in electron density in between. Representative plots of electron density are shown in Fig. 1.4. Two good sources of further information about the ionosphere are those by Rishbeth and Garriot (1 969) and Ratcliffe (1969).

D Region

The D region, the lowest of the ionospheric regions, extends from approximately 50 to 90 km with the maximum electron

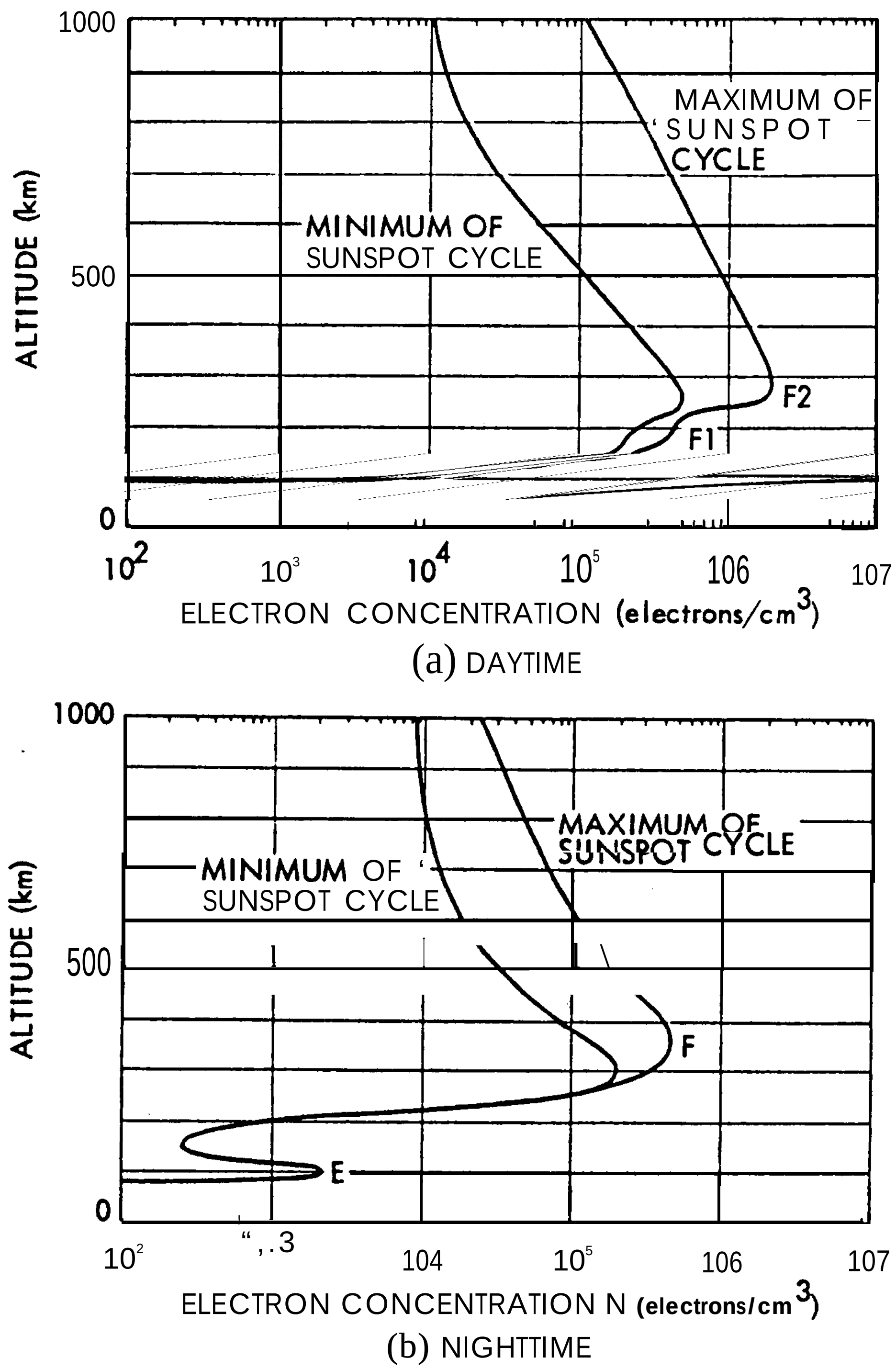

Figure 1.4 Electron densit y distribution at the extremes of the sunspot cycle (from Hanson, W. B., "Structures of the Ionosphere" in Johnson, F.S. (cd.), Satellite Environment Handbook, Stanford U. Press, 1965).

electron density of about $10^9/m^3$ occurring between 75 and 80 km in the daytime. At night electron densities throughout the D region drop to vanishingly small values.

As the electron concentration in the D region is very low, it tends to have little effect on high-frequency waves. However, attenuation in the ionosphere occurs mainly through collisions of electrons with neutral particles, and as the D region is at a low altitude many neutral atoms and molecules are present and the collision frequency is high. Therefore transmissions in the AM broadcast band are highly attenuated in the day time in the D region, but distant reception improves at night when the D region disappears.

E Region

The E region extends from about 90 to 140 km, and the peak electron concentrate ion occurs between about 100 and 110 km. Electron densities in the E region vary with the 1 i-year sunspot cycle and maybe about $10^{11}/m^3$ at noonat the minimum of the solar cycle and about 50 percent greater at the peak of the cycle. Electron concentrations drop by a factor of about 100 at night, Intense electrical currents flow in the equatorial and auroral ionospheres at E-region altitudes, these currents being known as equatorial and equatorial electrojets. Radio waves are scattered from electron density structure associated with the electrojets at frequencies up to more than 1000 MHz. Backscatter echoes from- the auroral electrojets indicate the regions of occurrence of aurora and are referred to as radio aurora. The phenomena of sporadic E, thin, sporadic, often discontinuous layers of intense ionization, occurs in the E region, at times with electron densities well above $10^{12}/m^3$. The E layer is useful for communications, as HF waves may be reflected from the E layer at frequencies which are a function of time of day and period of the sunspot cycle. By causing interference between VHF stations, sporadic E tends to be a nuisance.

F Region

The F region has the highest electron densities of the normal ionosphere. It somet imes consists of two parts, the F_1 and F_2 layers. The F_1 layer largely disappears at night but has peak densities of about 2.5 $\times 10^{11}/m^3$ at noon at the minimum of the solar cycle and 4 $\times 10^{11}/m^3$ at noon at the peak of the solar cycle. The F_2 layer has the highest peak electron densities of the ionosphere and the electron densities there remain higher at night than in other regions. The peak electron density is in the 200-. to 400-km height range and may be between about 5 x $10^{11}/m^3$ and 2 x $10^{12}/m^3$ in the daytime and between 1 x $10^{11}/m^3$ and 4 x $10^{11}/m^3$ at night. Reflection from the F_2 layer is the major factor in HF communications which formerly handled a large fraction of long-distance, especially transoceanic, communications,

Plasmasphere and Magnetosphere

The upper limit of the ionosphere is not preciselv defined but for the purposes of space communications may be taken as 2000 km, this being the upper limit for significant Faraday rotation (Sec.2.2). Above the ionosphere is the plasmasphere or protonosphere, which has an electron content of about 10 percent of the ionospheric content in the daytime "and up to 50 percent of the ionospheric content at night, as defined along an earth-space path.

The Earth's magnetic field is confined inside an elongated cavity in the solar wind, that extends to about 10 earth radii in the direct ion towards the Sun and has a long tail extending to about 50 earth radii or farther in the opposite direction. The boundary of this cavity is known as the magnetopause, and the region inside the boundary, above the ionosphere, is known as the magnetosphere. The magnetosphere can be defined as the region in which the Earth's field dominates the motion of charged particles, in contrast to the ionosphere where collisions play a major role. The Van Allen radiation belts, discovered in 1958 by use of Explorer 1, are in the magnetosphere. The plasmasphere, usually considered to be above the ionosphere (or above 2000 km), is below the Van Allen belts and is the lowest region of the magnetosphere. The plasmasphere is bounded on the upper side at about 4 earth radii at the equator by the plasmapause where the plasma density drops by a factor of 10 to 100 or from about. 108\m3 to $10^6/m^3$.

Irregularities and Disturbed Conditions

A brief description has been provided of the ionospheric layers. Consideration of the ionosphere" can be separated into the quiet ionosphere and ionospheric disturbances and irregularities, as occur at times of magnetic storms and essentially every night to some degree in the auroral and equatorial ionospheres. Both propagation in the quiet ionosphere and the effects of disturbances and irregularities are considered in the following Chap. 2.

1.4 NATURAL REGIONS OF THE EARTH, A GLOBAL VIEW OF PROPAGATION EFFECTS

The uneven heating of the Earth's surface by the Sun, the rotation of the Earth and the consequent Coriolis force, and surface features of the Earth determine a characteristic pattern of wind over the Earth, See, for example, a text on meteorology such as that by Dorm (1975), p. 238. In good measure because of this pattern, corresponding characteristic patterns of climate, ecosystems, vegetation, tropospheric refractivity (Sec. 3.1), and rainfall (Chap. 4) also occur over the surface of the Earth. The living portions of ecosystems are referred to as biotic communities, and the major terrestrial biotic communities are known as biomes. For practical purposes the biomes can be referred to simply as natural regions. Maps of the natural regions of all the continents are included in the Aldine University Atlas; (Fullard and Darley, 1969). The climatological, ecological, and geographical characteristics of a region are closely related and are pertinent to satellite communications. Areas of tropical forest, which are rapidly disappearing, can be expected to have heavy rainfall and a high atmospheric water vapor content. The Arctic, on the other hand, has low precipitation and low values of water vapor.

Global models for estimating rainfall statistics have been developed and are discussed in Sec. 4.3.3, where rain rate regions are shown in Figs. 4.8 - 4.10 and Figs. 4.13 - 4.15. The regions shown are in rough correspondence with the natural regions of Fullard and Darley (1969) and also with the Koppen system for classifying climates (Trewartha, 1968). The global models are not very detailed, however, and advantage should be taken of any more detailed information that may be available.

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